Robust Multi-User Analog Beamforming in mmWave MIMO Systems

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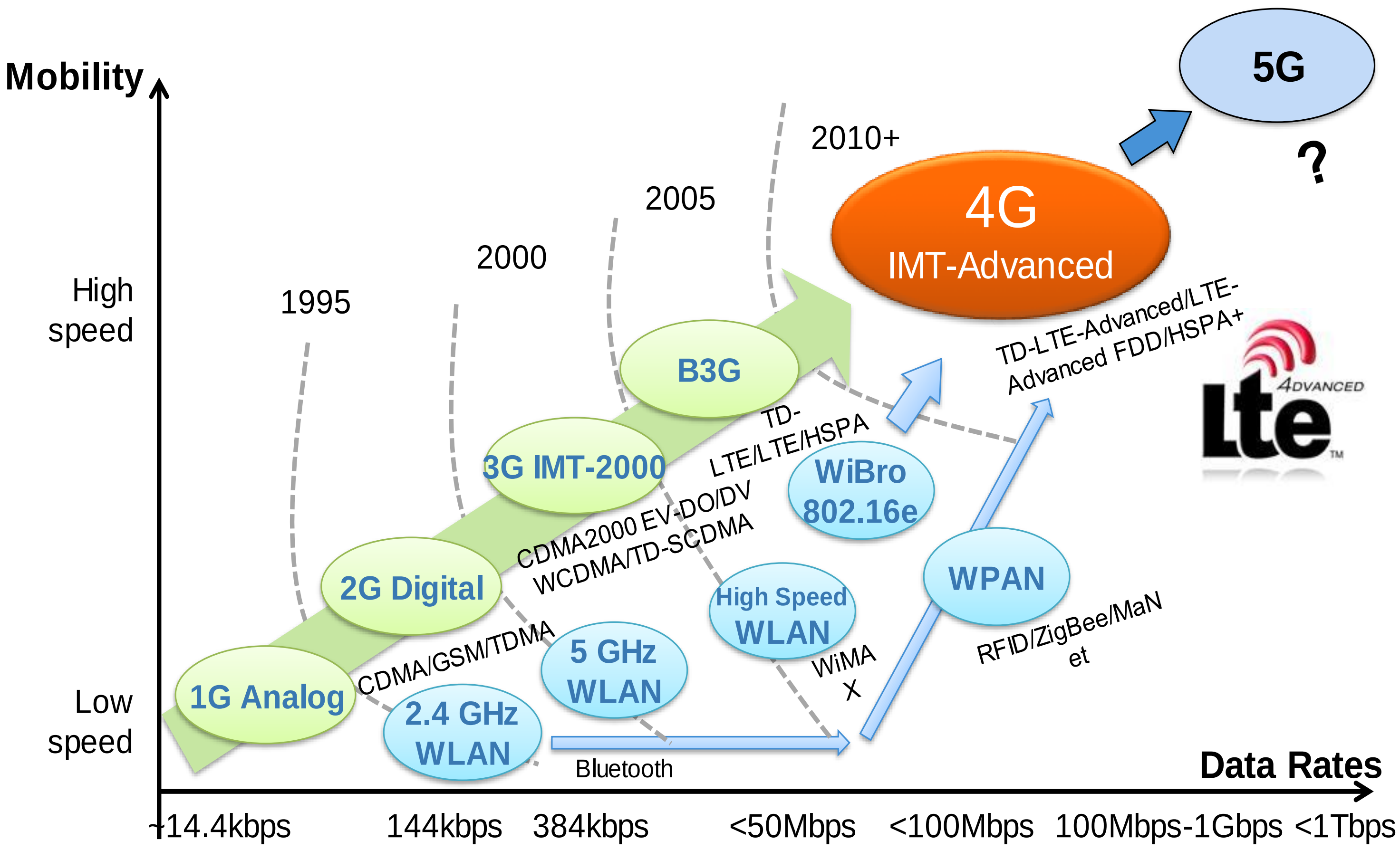
Background



5G

- 1000 times the system capacity and 10 times the spectrum efficiency

mmWave

- Key technology
- High data rate and spectrum efficiency

MU-MIMO

- Higher system throuput

MU-MIMO beamforming in mmWave

Hybrid

- **Good performance**
- **Large feedback overhead**

Analog

- **Easy to implement and small feedback overhead**
- **No interference cancellation**
- **Advantageous over MU-MIMO**

Imperfect CSI

- **No existing robust analog beamforming design**

Our goal

- Suppress interference and enhance beamforming gain simultaneously
- Provide robustness

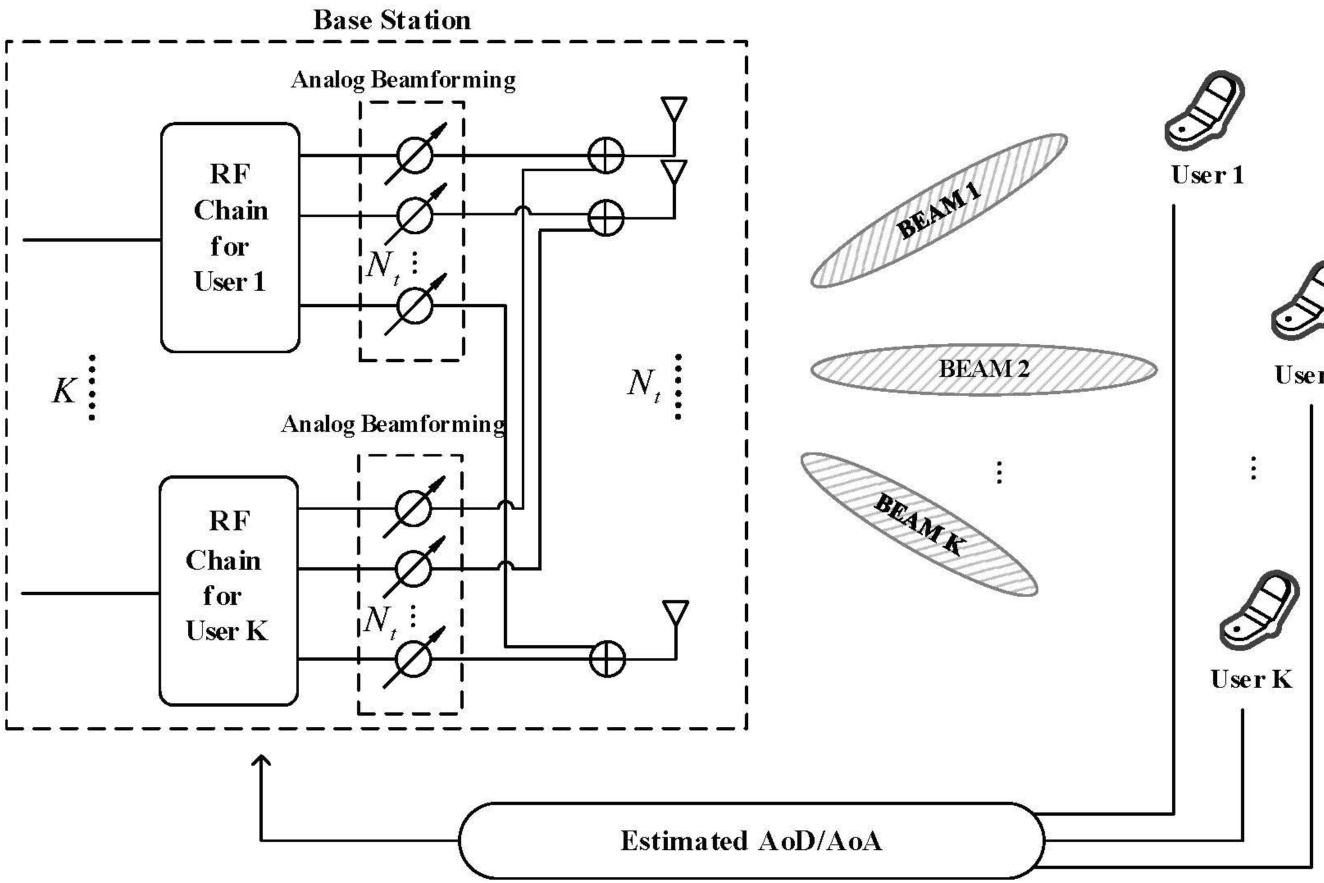
Challenges and solutions

Tradeoff between interference and beamforming gain

- Establish Multi-objective problem
- Find the best weight assignment

Robust design

- Develop channel error model
- Introduce the stochastic approach



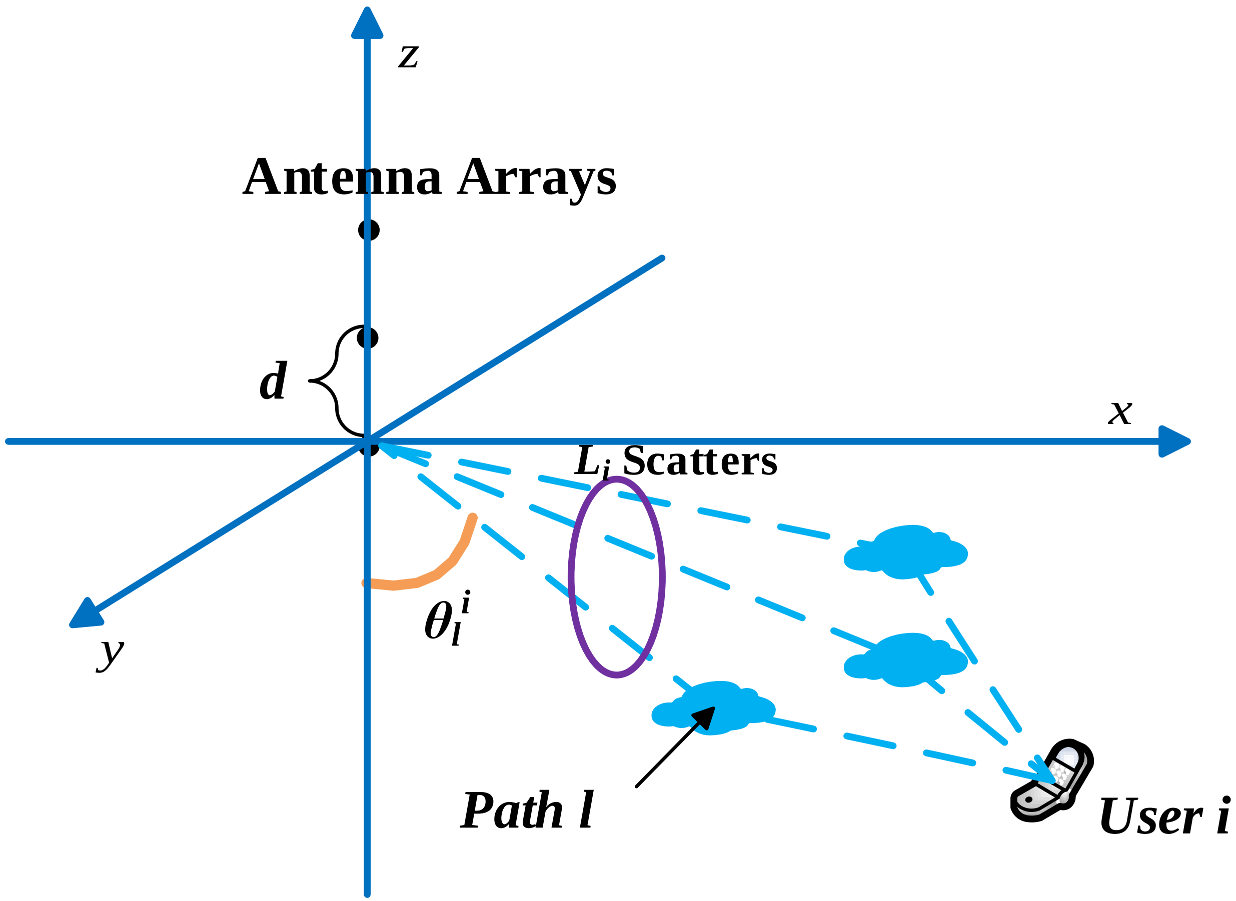
Signal model

$$y_i = h_i^H w_i s_i + \sum_{k=1,k\neq i}^{K} h_i^H w_k s_k + n_i \quad (1)$$

Leakage Interference

$$Leakage = \sum_{k=1,k\neq i} |h_k^H w_i|^2 = w_i^H \tilde{\mathbf{I}}_i^H \tilde{\mathbf{I}}_i w_i \quad (2)$$

System model



Clustered channel model

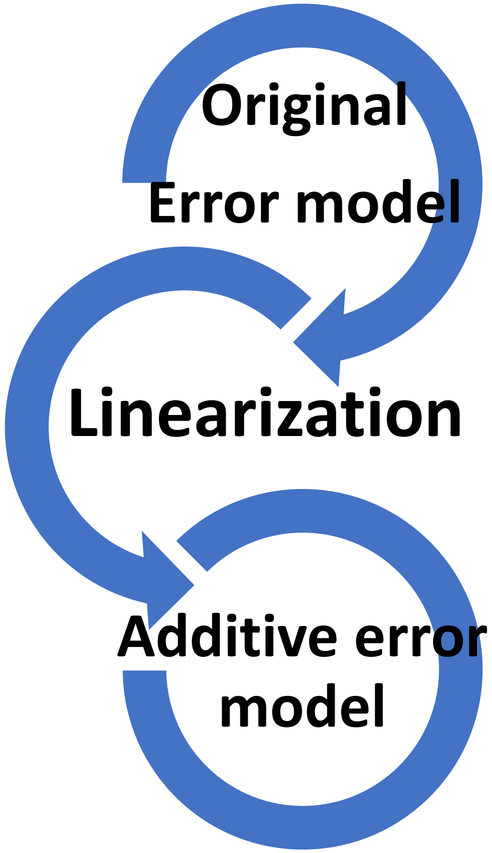
$$h_i^H = \sqrt{\frac{N_t}{L}} \sum_{l=1}^{L} (a_l^i)^* \alpha_t(\theta_l^i)^H = \tilde{h}_i^H \underbrace{\mathbf{A}_i^H}_{AoD\ matrix} \quad (3)$$

Array response vector for ULA

$$\alpha_t(\theta_l^i) = \frac{1}{\sqrt{N_t}}[1, e^{j\frac{2\pi}{\lambda}d\sin(\theta_l^i)}, ..., e^{j(N_t-1)\frac{2\pi}{\lambda}d\sin(\theta_l^i)}]^T \quad (4)$$

Channel model

Channel Error Model



$$\alpha(\theta_l^i + \Delta\theta_l^i) = \frac{1}{\sqrt{N_t}}[1, e^{j\frac{2\pi}{\lambda}\underline{dsin(\theta_l^i+\Delta\theta_l^i)}}, \ldots, e^{j(N_t-1)\frac{2\pi}{\lambda}\underline{dsin(\theta_l^i+\Delta\theta_l^i)}}]^T \tag{4}$$

$$e^{jn\kappa\sin(\theta_l^i+\Delta\theta_l^i)} = e^{jn\kappa\sin(\theta_l^i)} + \underbrace{jn\kappa\cos(\theta_l^i)\Delta\theta_l^i e^{jn\kappa\sin(\theta_l^i)}}_{e_l^{i,n}} \tag{5}$$

$$\begin{cases} \tilde{\alpha}(\theta_l^i) = \alpha(\theta_l^i + \Delta\theta_l^i) \approx \alpha(\theta_l^i) + e_l^i & (6) \\ \mathbf{A}_i = \mathbf{A}_i^p + \mathbf{E}_i & (7) \\ \tilde{\mathbf{I}}_i = \tilde{\mathbf{I}}_i^p + \tilde{\mathbf{E}}_i & (8) \end{cases}$$

Problem Formulation

Interference suppression:

- Leakage Probability (restriction)

$$P_{leakage} = \Pr\{w_i^H \tilde{\mathbf{I}}_i^H \tilde{\mathbf{I}}_i w_i \leq \gamma_i\} \quad (9)$$

Average beamforming gain:

- Expectation

$$BG_{avg} = E[w_i^H \mathbf{A}_i \mathbf{A}_i^H w_i] \quad (10)$$

Problem formulation

$$w_i^{opt} = \{E[w_i^H \mathbf{A}_i \mathbf{A}_i^H w_i], Pr\{w_i^H \tilde{\mathbf{I}}_i^H \tilde{\mathbf{I}}_i w_i \leq \gamma_i\}\}$$
$$s.t.\ w_i \in \mathcal{W}, \tag{11}$$

Challenge 1	The probability restriction
Challenge 2	How to deal with the MOP
Challenge 3	The non-convex constraints

Dealing with the probabilistic restriction

Using Markov's inequality to transform the probabilistic restriction to a deterministic objective

$$\Pr\{w_i^H \tilde{\mathbf{I}}_i^H \tilde{\mathbf{I}}_i w_i \le \gamma_i\} = \Pr\{w_i^H (\tilde{\mathbf{I}}_i^p + \tilde{\mathbf{E}}_i)^H (\tilde{\mathbf{I}}_i^p + \tilde{\mathbf{E}}_i) w_i \le \gamma_i\}$$
$$\ge 1 - \frac{E[w_i^H (\tilde{\mathbf{I}}_i^p + \tilde{\mathbf{E}}_i)^H (\tilde{\mathbf{I}}_i^p + \tilde{\mathbf{E}}_i) w_i]}{\gamma_i}$$
$$= 1 - \frac{Tr(((\tilde{\mathbf{I}}_i^p)^H \tilde{\mathbf{I}}_i^p + \tilde{\mathbf{C}}_i)\mathbf{W})}{\gamma_i}, \quad (12)$$

$$\mathbf{W} = w_i w_i^H$$

Problem reformulation

$$
\mathbf{W}^{opt} = \{Tr((\mathbf{A}_i^p(\mathbf{A}_i^p)^H + \mathbf{C}_i)\mathbf{W}), \left(1 - \frac{Tr(((\tilde{\mathbf{I}}_i^p)^H\tilde{\mathbf{I}}_i^p + \tilde{\mathbf{C}}_i)\mathbf{W})}{\gamma_i}\right)\}
$$

$$
\begin{aligned}
s.t.\quad & \mathbf{W}_{ii} = \frac{1}{N_t},\ \forall i = 1, ..., N_t; \\
& \mathbf{W} \succeq 0; \\
& rank(\mathbf{W}) = 1;
\end{aligned}
$$

non-convex constraints → linear constraints

Multi-objective problem — **Weighted-sum method**

Rank-one constraint — **Semi-definite relaxing**

- SDP

$$SDP(\mathbf{W}^{opt}) = \{\lambda_1 \left(1 - \frac{Tr(((\tilde{\mathbf{I}}_i^p)^H \tilde{\mathbf{I}}_i^p + \tilde{\mathbf{C}}_i)\mathbf{W})}{\gamma_i}\right) + \lambda_2 Tr((\mathbf{A}_i^p (\mathbf{A}_i^p)^H + \mathbf{C}_i)\mathbf{W})\}$$

$$s.t.\ \mathbf{W}_{ii} = \frac{1}{N_t},\ \forall i = 1, ..., N_t;$$

$$\mathbf{W} \succeq 0;$$

$$rank(\mathbf{W}) = 1,$$

- SDR

$$SDR(\mathbf{W}^{opt}) = \{\lambda_1 \left(1 - \frac{Tr(((\tilde{\mathbf{I}}_i^p)^H \tilde{\mathbf{I}}_i^p + \tilde{\mathbf{C}}_i)\mathbf{W})}{\gamma_i}\right) + \lambda_2 Tr((\mathbf{A}_i^p (\mathbf{A}_i^p)^H + \mathbf{C}_i)\mathbf{W})\}$$

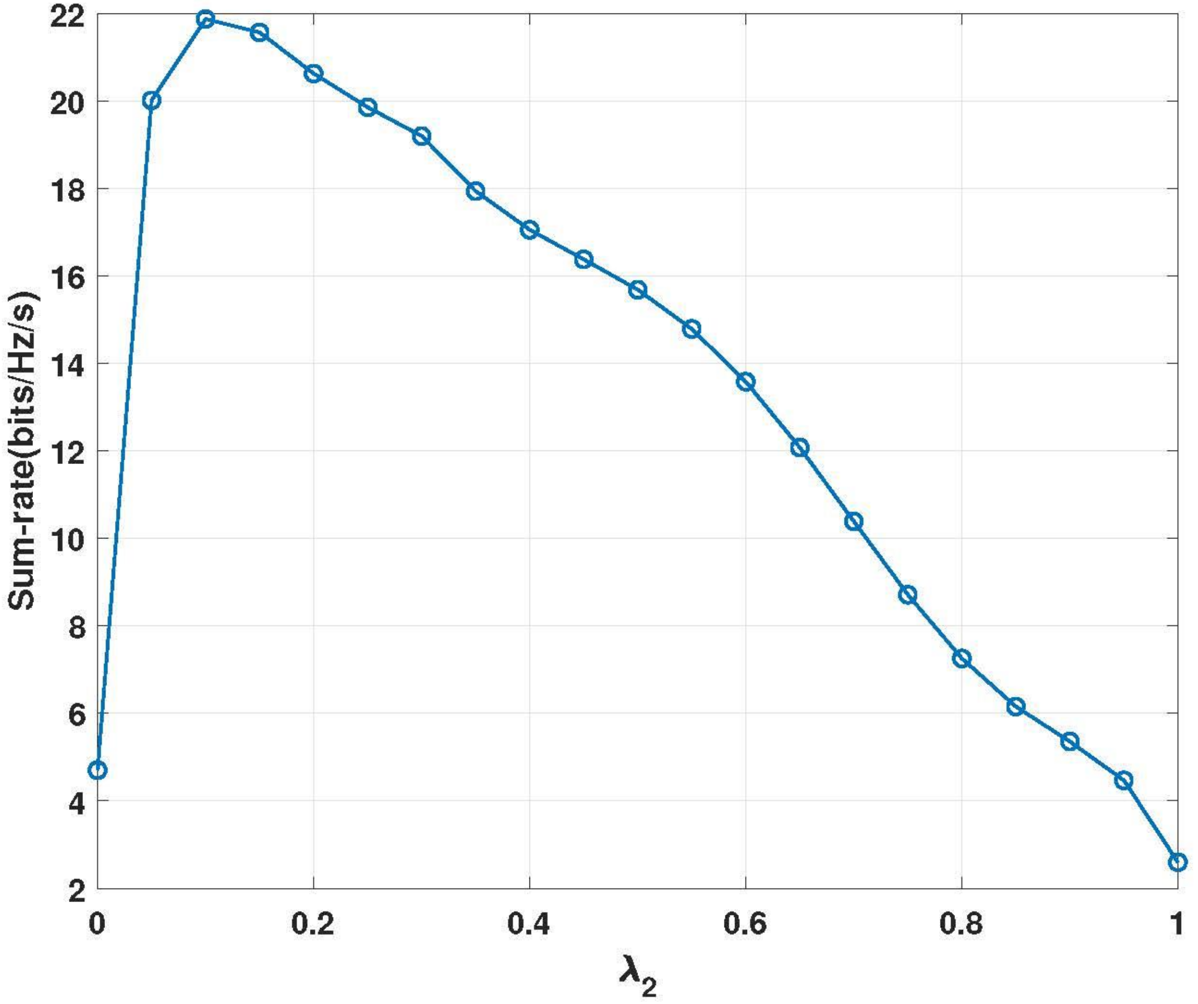
$$s.t.\ \mathbf{W}_{ii} = \frac{1}{N_t},\ \forall i = 1, ..., N_t;$$

$$\mathbf{W} \succeq 0.$$

- SDR can be efficiently solved
- Approximation is needed

Simulation

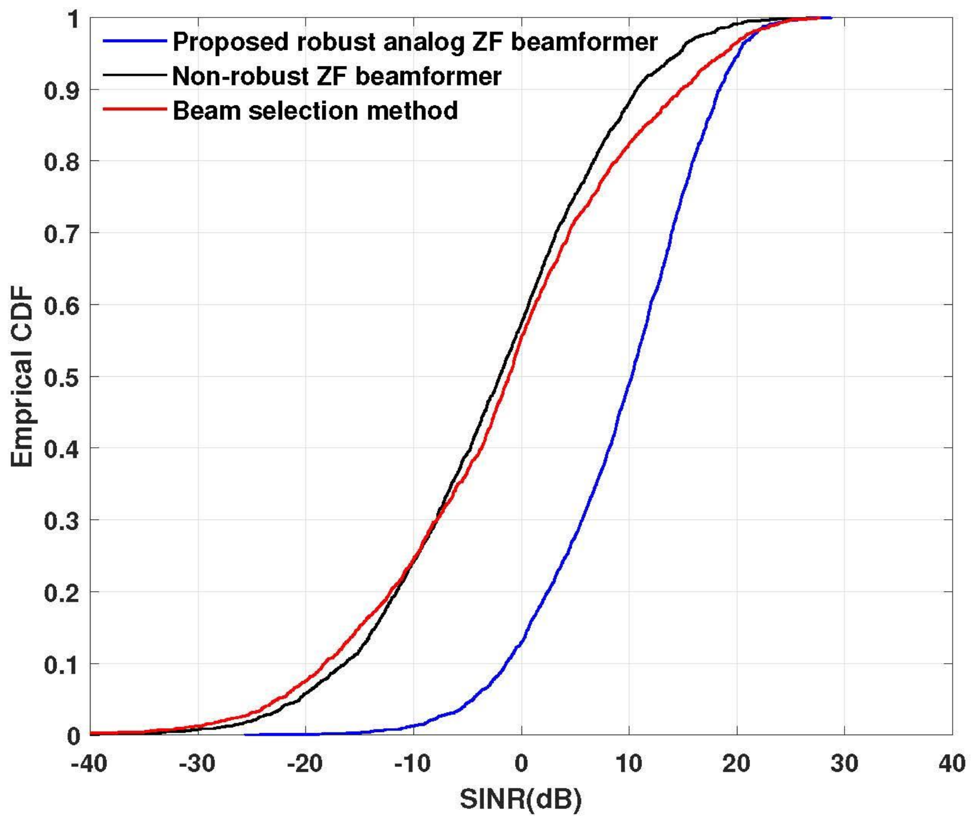
Methods	Imperfect channel model
Fully-digital ZF	$\tilde{h}(\mathbf{A}_i^p + \mathbf{E}_i)$
Beam Selection	$\Delta\theta_i$ in beam alignment with mean 0 and variance σ_i
Our proposed method	$\mathbf{A}_i^p + \mathbf{E}_i$

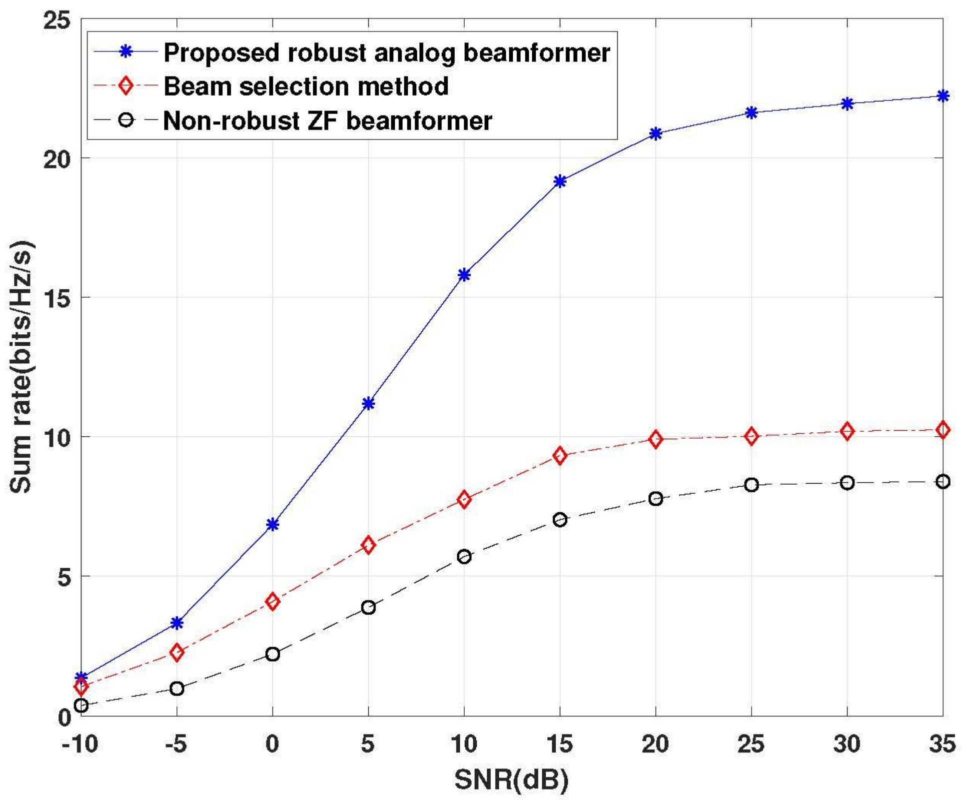


- **Strike a balance in terms of sum-rate**

Best weight searching

Performance comparison





Summery

Developed a channel error model for the scattering clustered channel model, which can serve as a general channel error model for mmWave channels

Proposed a robust analog beamforming scheme for mmWave systems to alleviate the effects of the channel estimation and feedback quantization errors

The proposed robust analog beamforming scheme brings about 109% improvement in sum-rate compared to the conventional beam selection method.

Thanks